

Lead acid batteries in solar refrigeration systems

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Abstract

Batteries play a vital role in solar photovoltaic refrigeration systems. Despite breakthroughs in operational characteristics of various components of such systems, lead acid batteries continue to be the only viable electrical energy storage devices as of date. The purpose of this paper is to report the results of characterization of a lead acid battery system as a component of a small capacity uninterrupted refrigeration system. The charging characteristics on solar energy, mains and a generator set powered by an internal combustion engine are presented. It is shown that through a judicious choice of capacity and load matching, the maximum power point tracker can be eliminated.

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1. Introduction

The battery bank plays a very important role in a solar photovoltaic (PV) refrigeration system. In general, a PV charged battery bank has a significantly different role as compared to conventional grid connected battery banks [1]. In addition to the primary role as energy storage devices, they also provide a power buffer between PV array and load. They do add to system complexity and the overall cost. Yet, an optimal choice could result in an excellent energy inventory and management of the overall power system, with high reliability, low maintenance costs, long life time, high charging efficiency and high voltage stability. The para-

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meters affecting optimization are the storage capacity, the operating voltage and matching with the load it is expected to meet. This paper will focus on the battery bank in a small capacity solar PV refrigeration system. The refrigerator used in the experiment has an internal volume of 165 l having a cooling capacity of 100 W, powered by a hermetic compressor operating on 220 V, 50 Hz AC. A complete electrical and thermal characterization of this refrigerator has been reported already [2,3]. A typical domestic refrigerator has a periodic load with an on-cycle of about 10 min and an off-cycle of 10–20 min under normal operating conditions. This could be low during the day when the door is opened often and since the ambient temperature in the environment could be high. It could be higher during the night. At start, large currents are drawn, typically 8–10 times the running currents. A current relay switches the flow of current through starting and running windings at the time of start to running winding during steady operation of the compressor motor. The starting transients stretch for no more than a fraction of a second (200–850 ms) and depend on the wave form and magnitude of the voltage [2]. An inverter is the other essential component of the overall system. Due to the withdrawal of large currents at start, the battery voltage tends to drop steeply. The PV system that powers this refrigerator in our case is an array of eight modules with a set of two in series and four such pairs in parallel. These modules have a notional output of 30 W with an open circuit voltage of about 30 V. The complete characterization of this array has also been reported in our earlier papers [4,5]. The performance test results were presented in [6,7]. The key features of the design of a control system were described in [8]. The objective of this paper is to present the basis for the choice of the battery bank and results of its characterization studies.

2. Description of the electrical energy storage system

The battery bank consists of a set of four 6 V, 180 Ah deep discharge tubular lead acid batteries. Each battery has three cells of 2 V each. All the four batteries were connected in series to give a nominal output of 24 V. This option was chosen instead of two in series and two in parallel because of the need to reduce the magnitude of currents handled by the inverter, which has a strong bearing on the overall losses. In view of this voltage, the PV panels were arranged in two in series, four such units in parallel configuration. Charging was possible more or less from dawn to dusk. Trickle charging is possible even with low sunshine such as within half an hour of sunrise and up to half an hour before sunset and also on cloudy days. Appendix A gives a calculation scheme for arriving at the battery storage capacity. The electrical characterization of the refrigerator shows [2] that there exists an optimal voltage for the wave form generated by the inverter at which the power consumption of the refrigerator is the least. As a result, it would be preferable to ensure that the battery voltage is commensurate with the corresponding input voltage of the inverter. The state of charge (SOC) of the battery should be such that discharge does not cause major drifts in the battery open circuit voltage. Ideally this would occur at $\text{SOC} > 0.5$. Further, it is seldom possible to keep the

SOC at 1. Through trial and error and prolonged experimentation, it was concluded that $0.5 < \text{SOC} < 0.8$ would be ideal for the battery bank. The lower limit is in tune with the findings of Lancashire [9] and Calloway [10], who observed that life expands to more than 4000 charge/discharge cycles at 60% SOC or more than 2000 cycles at 40% SOC. The upper limit arises out of heating effects and gassing [11]. The manufacturer's recommended charging current is 9 A, although no damage is caused even up to charging currents of 18 A. The next section describes the outcome of studies on the characterization of the battery. The charging and discharging characteristics were obtained for the cases when the battery bank was charged from conventional mains, a generator set and PV panels with two, three and four pairs of panels charging it.

3. Results and discussion

In the first instance, a relation between the SOC and the battery voltage under load conditions and the specific gravity of the electrolyte was obtained. Fig. 1 shows the results. The voltage and the specific gravity are linear functions of SOC. This information was necessary to specify the limits in the algorithm for control described in [8].

Fig. 2 shows the variation of battery voltage and electrolyte temperature during charging from mains. The refrigerator was allowed to run through the battery–inverter during this charging process. The upper and lower wings of the battery voltage plot correspond to off- and on-cycle states of the refrigerator, respectively. It may be observed that the battery temperature increases rapidly beyond a no load open circuit voltage at about 27 V. To maintain the temperatures within reasonable limits, after about 500 min the charging current was reduced manually.

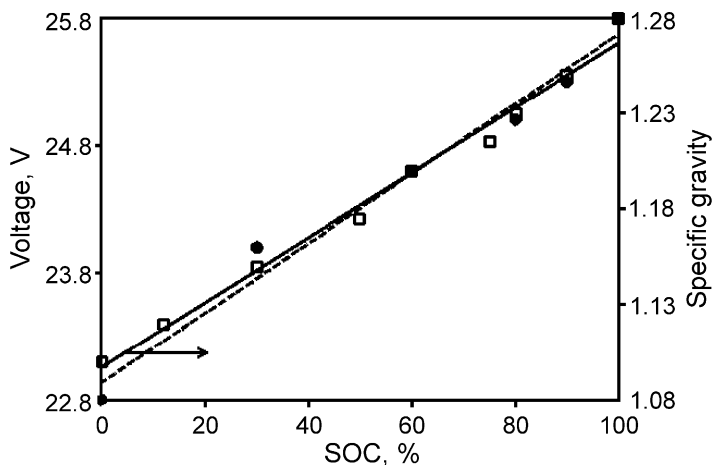


Fig. 1. On-load battery voltage and electrolyte specific gravity variation with battery state of charge. Legend: □ specific gravity (right ordinate); ● voltage (left ordinate).

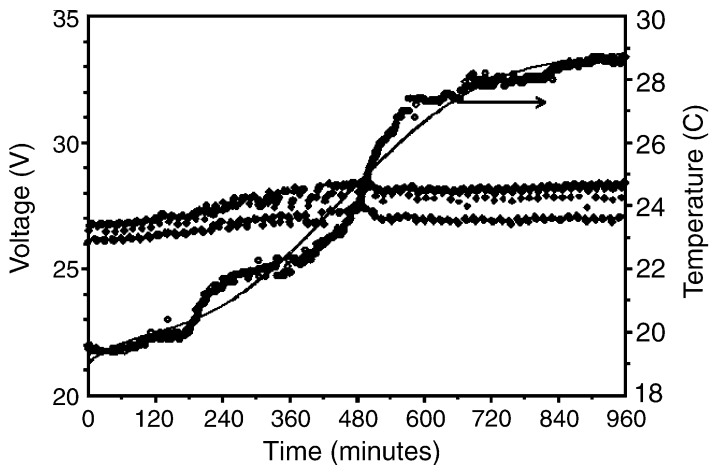


Fig. 2. Battery voltage and electrolyte temperature variation during on-load charging. Legend: + voltage (left ordinate); o temperature (right ordinate).

This is seen as a dip in the battery voltage. Yet, the voltage increases steadily. But the battery temperature shows first order behavior due to its large thermal mass. Hence, for the overall system control algorithm, the battery temperature is also an input along with the battery voltage. SOC arising out of the battery voltage should be complemented with the temperature information. The charging current needs to be reduced if the electrolyte temperature starts rising. This could happen if continuous sunny days occur while charging with PV panels. Such control will reduce release of gas by the battery and the consequent loss of battery electrolyte.

Based on diurnal variation of insolation, it was observed that about 1520 W h of energy can be collected per sunny day by the field being experimented with [3]. Thus, about 160 W h per day (equivalent to 6.7 Ah) can be stored by the battery. This would lead to an SOC of 100% if there are over 18 continuous sunny days if the first day SOC is about 0.3 under normal working conditions of the refrigerator. The controller mentioned earlier [8] enables disconnection of the appropriate number of pairs of panels from the battery to avoid overcharging. This is pursuant to the observation that for $\text{SOC} > 0.8$ heating effects would dominate and hence the charging current will have to be reduced after 13 continuous sunny days. Fig. 3 shows the voltage and current variations when solar panels of different configurations of utilization (i.e. four, six and eight panels) are connected to the 180 Ah battery bank without any load on the battery. When the $\text{SOC} > 0.8$ and continuous sunny days exist, an appropriate number of panels were disconnected progressively using a control system [8].

Fig. 4 shows the battery charging characteristics with mains and generator via a rectifier. In both the cases, high charging currents (>10 A) have been used. The figure corresponds to charging from $\text{SOC} < 0.05$ where the open circuit voltage (OCV) was 23.2 V. Immediately after the charging process commences, the battery

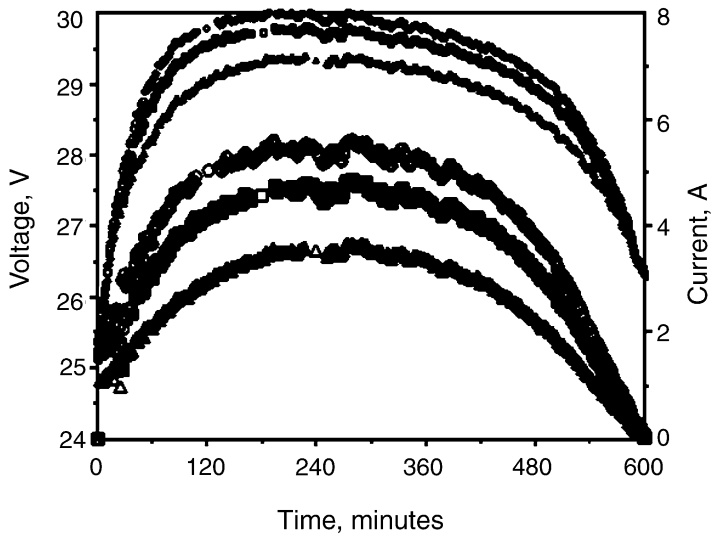


Fig. 3. Diurnal variation of battery voltage and charging current under no load with four, six and eight panel configuration. Legend: $\circ$ four panels; $\square$ six panels; $\triangle$ eight panels; larger symbols (current), right ordinate; smaller symbols (voltage), left ordinate.

voltage rises to 26 V in both the cases. With the charging from mains, the voltage keeps increasing steadily and reaches over 27.5 V after 10 h, whereas the current is fairly steady for the first 3 h and then gradually decreases to 13–14 A as the battery charge level increases.

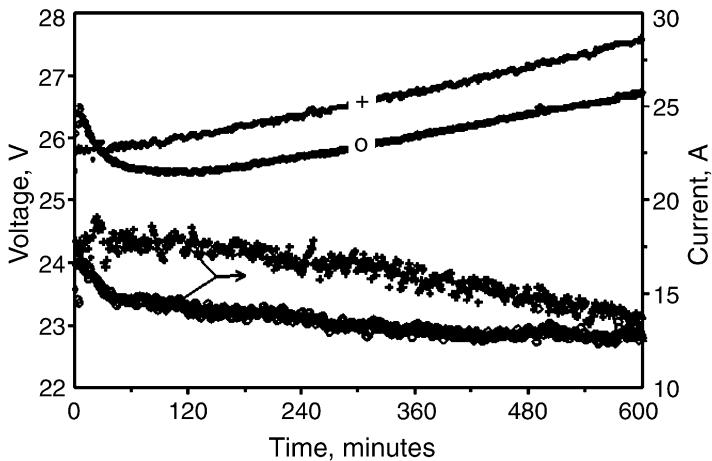


Fig. 4. Charging characteristics of battery from mains and generator set. Legend: $+$ mains; $\circ$ generator; larger symbols (current), right ordinate; smaller symbols (voltage), left ordinate.

In the case of charging from the 1 kV A generator set, the characteristic curve is somewhat different. The OCV drops exponentially after a quick rise to stabilize at about 25.5 V after 1 h. Then it increases to 27.7 V at the end of 10 h. The current, though over 16 A at the start, also declines. This could be attributed to the air-cooled two stroke kerosene engine taking a long time to reach steady state operating conditions. Though this time seems to be long, it is not unusual for equilibrium to take that long to achieve due to mechanical and thermal inertia of the system, increase in lubricant temperatures, etc. After engine equilibrium is attained, the rise in OCV is exactly the same as in the case of mains and the decline of charging current is also commensurate with that of mains.

The above results are necessary to enable the controller to source alternate charging methods in the event of continuous cloudy days. Such conditions prevail during the monsoon. The controller looks for the mains as the first preferred source, failing which it advises start of the generator set. It takes about 10 h to fully charge the battery. A fully charged battery provides a backup of 3 days when it discharges to an SOC of 0.2.

In PV charged battery banks, often a maximum power point tracker (MPPT) is introduced so that all the power available from the panels can be used. However, in the present system, the choice of the battery capacity and the nature of load have obviated the need for an MPPT. Although it is often felt that solar energy and refrigeration are naturally matched loads, it was shown earlier [5] that the optimum voltage of the panels where the maximum power is available reduces significantly a few hours either side of noon due to increase in the temperature of the PV cells. This drop could be as much as 26–24 V for an eight panel configuration. However, battery voltage variation is out of phase with the optimum voltage in both the cases with and without load on the panel + battery system. Thus, a small mismatch loss appears to be inevitable for most part of the maximum sunshine hours. Fortunately, from Fig. 5, which depicts the power generated by the PV array (expanded at the maximum power point), it can be seen that for the levels of voltage of the battery with the refrigerator as load, the loss of power is no more than 6 W.

In this particular instance, at the start of the day, the battery OCV was around 26 V, which corresponds to an SOC of higher than 0.7. Under load it drops to about 25 V. Even under these conditions, the power loss due to mismatch is no more than 4%. If the battery SOC were to be lower than 0.5, this mismatch loss would have diminished further. For this reason, it has been decided to couple the battery bank directly to the PV array without the use of an MPPT. This strengthens our conviction that the battery should be operated at $0.5 < \text{SOC} < 0.8$ when charged from the PV panels. Direct coupling of the array and the load is recognized to be simple, cheap and reliable for different PV systems.

Recalling that the power consumption of the MPPT is about 7% of the power generated [12], it is prudent to eliminate it because the power loss is likely to be less than this figure. There is a reasonable plateau on the power curve within 2 V of optimum voltage on either side, over which the power loss due to shift from the optimal point is smaller than what it would have been had an MPPT been used. In

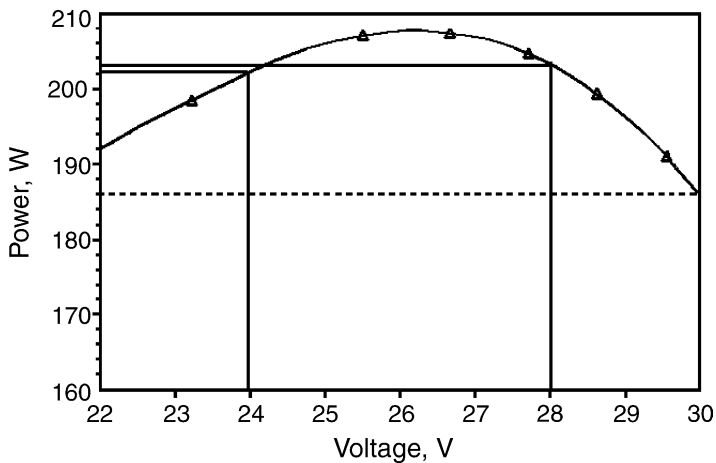


Fig. 5. Expanded power–voltage relation for the ensemble depicting possible loss of power due to fluctuation of the battery voltage on-load and no load.

the present case, dispensing with the MPPT considerably reduced the system complexity and the associated maintenance problems. An important precaution to be taken is that the panels must be kept dust free. The effects of accumulation of dust on the performance of the panels is analyzed in detail in [5]. In general, the effect of dust is to sharpen the peak power point.

The feature of recovery of the battery voltage during the off-cycle of the refrigerator and the discharge characteristics of the battery were already reported [7]. To achieve these optimal operating conditions, the battery was disconnected from the inverter during the refrigerator off-cycle.

The findings of this study are corroborated by a recent study by Cherif et al. [13] who also conclude that to protect the battery from deep discharge and sulfation the load and power consumption must be controlled. To voltage output must be fixed as a function of the discharge current. They also show that a regulator is insufficient to prevent ageing and optimal management and monitoring are essential.

4. Conclusions

In this paper, the importance of the choice of battery capacity to match the nature of the refrigerator load in a PV refrigeration plant has been brought out. Charging with various power sources and discharging under various conditions are presented. The MPPT can be dispensed with if system sizing is done appropriately. The battery performance characteristics must form an important input for the control algorithm. The results are in conformity with some of the recent findings on standalone PV systems.

Acknowledgements

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Appendix A. Calculation of battery capacity for PV refrigeration system

Approximate daily energy consumption of refrigerator [2]	1000 W h
Parasitic consumption of inverter and controls [8]	360 W h
Total daily need	1360 W h
Operation needs during night/low insolation hours	800 W h
For a 24 V battery bank, minimum storage needs = $800/24$	33 Ah
For $0.5 < \text{SOC} < 0.8$ the required battery capacity	110 Ah

A 24 V 110 Ah battery bank would be adequate if continuous sunny days are present. However, if the whole day is cloudy, battery drain = $1360/24 = 57$ Ah. For $0.5 < \text{SOC} < 0.8$, battery capacity = 190 Ah. We chose 180 Ah, the nearest available capacity in our experiments.

References

- [1] Steffens F. Solar energy: battery energy storage and control. *Journal of Power Sources* 1991;35:1–20.
- [2] Kattakayam TA, Srinivasan K. Electrical characterization of domestic refrigeration compressors. *IEE Transactions Measurement, Science and Technology* 1997;144:123–6.
- [3] Kattakayam TA, Srinivasan K. Thermal performance characterization of a photovoltaic driven domestic refrigerator. *International Journal of Refrigeration* 2000;23:190–6.
- [4] Kattakayam TA, Khan S, Srinivasan K. Diurnal and environmental characterization of solar photovoltaic panels using a PC-AT add-on plug-in card. *Solar Energy Materials and Solar Cells* 1996;44:25–36.
- [5] Kattakayam TA, Srinivasan K. Experimental investigation on series parallel cluster of photovoltaic panels. *Solar Energy* 1997;61:231–40.
- [6] Kattakayam TA, Srinivasan K. Photovoltaic panel-generator based autonomous power source for small refrigeration units. *Solar Energy* 1996;56:543–52.
- [7] Kattakayam TA, Srinivasan K. Uninterrupted power supply for autonomous small refrigerators. *Energy Conversion and Management* 1998;39:21–6.
- [8] Kattakayam TA, Srinivasan K. Robust controller for an autonomous small refrigeration unit. *IEE Transactions Measurement, Science and Technology* 1999;146:159–63.
- [9] Lancashire SJ. Life cycle comparison of different battery types for use with photovoltaic systems. *IEEE PV Specialists Conference* 1988;2:1158.
- [10] Calloway TM. Autonomous photovoltaic-diesel power system design. 18th IEEE Photovoltaic Specialists Conference. 1985, p. 280.
- [11] Alminauskas V. Performance evaluation of lead acid batteries for use with solar panel. 23rd IEEE PV Specialists Conference. 1993, p. 1258.
- [12] Khouzam KY. The load matching approach to sizing PV systems with short term energy storage. *Solar Energy* 1994;53:403–9.
- [13] Cherif A, Jraidi M, Dhouib A. A battery ageing model used in PV stand alone system. *Journal of Power Sources* 2002;112:49–53.